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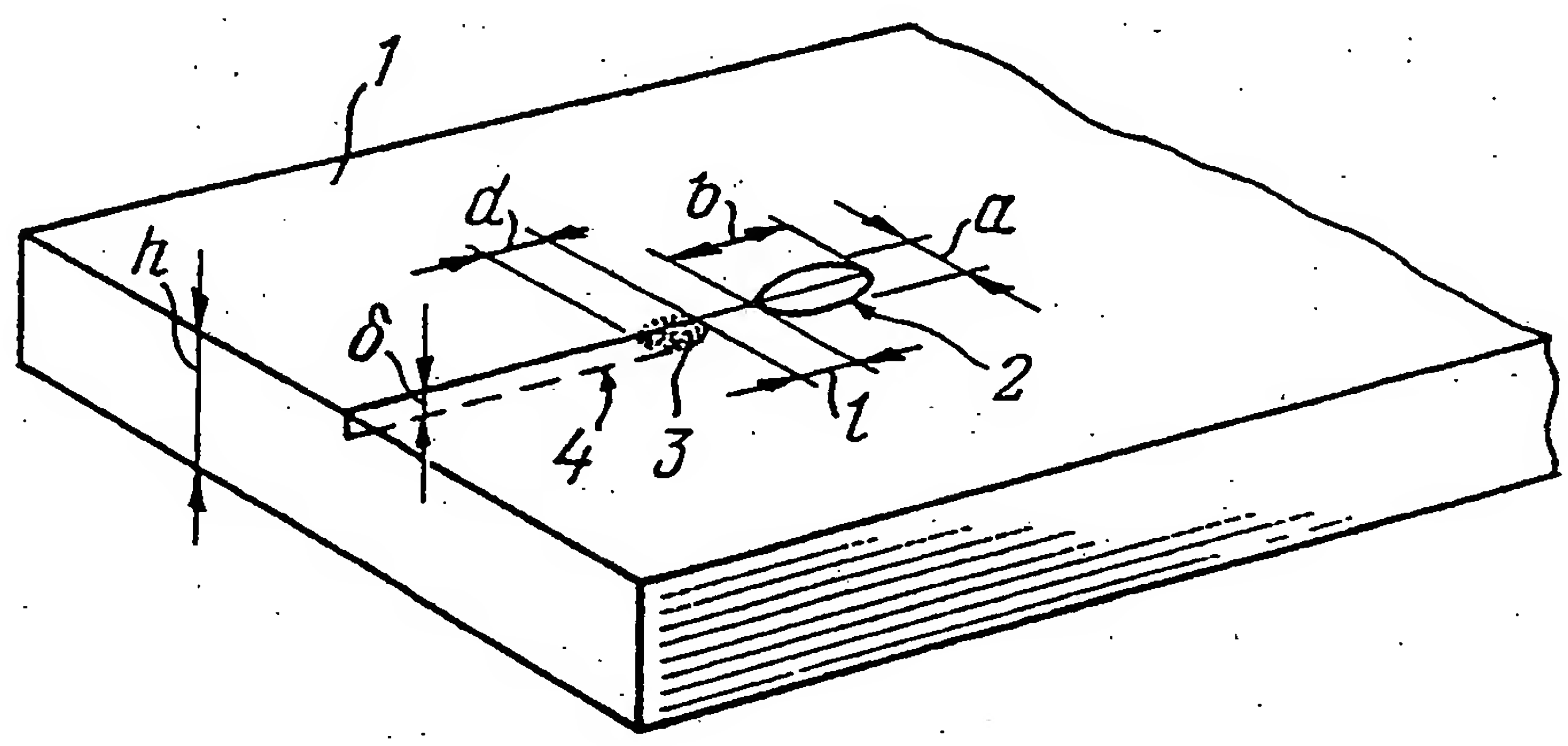

(57) Abstract

A method of cutting non-metallic materials, specifically glass, resides in the heating of the material by an incident beam of radiation being effected to a temperature short of its softening point, with the rate of relative displacement of the beam and of the material, and the region of the heated zone which is locally cooled being selected to form a blind crack in the material. The method provides for increasing substantially the cutting speed and accuracy, and also for controlling the depth, shape and angle of the cut face formed by the crack. The method can be employed in the automotive industry for making glass windows and mirrors, in the electronics industry for making precision backings and substrates for LED indicator panels and masks, magnetic and optomagnetic disks, in watch-making for making protective glasses, in the aircraft and space industry for making structural optics components, in construction and architecture for dimensional pattern-cutting of glass, including its integration in the glass manufacturing technology, and also in other fields of production and technologies where precision articles of non-metallic materials are made.

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SPLITTING OF NON-METALLIC MATERIALS

This invention relates to the splitting of bodies of brittle non-metallic material, such as glass.

It is known to work bodies of glass or other brittle non-metallic material by removing material therefrom by abrasion or scribing, using diamond or tungsten carbide tools. Such processes involve the expenditure of much time and skill, because they are basically manual.

GB-A-1 254 120 discloses a method of splitting bodies of glass or like material into two parts by a thermal shock process produced by intense local heating of the body by means of an incident beam of coherent radiation, and abstraction of heat from the heat-affected zone in order to produce thermal shock, which causes a crack to extend through the thickness of the body.

In this method the surface of a piece of plate glass is heated by a laser beam of radiation at 10.6 μm wavelength. Some of the beam energy is reflected, while most of it is absorbed and released as heat in a thin surface layer, as thick as one wavelength. The

compressive stress produced in the heated layer does not result, however, in the splitting of the glass. Further propagation of heat into the body of the glass is by thermal conduction. The splitting of the plate glass occurs as a considerable volume of the glass is heated up, and the thermally-induced stresses exceed its tensile strength. When a crack starts to form, the point of incidence of the laser beam is already displaced from the edge of the glass. Thus the evolution and propagation of the crack lags behind the movement of the laser spot. The rate of thermal splitting of the glass is rather low, and could not be increased by increasing the laser beam power, because as soon as this power exceeds a certain level, the glass becomes overheated, which is manifested by the formation of longitudinal and transverse microcracks along the line of heating.

The rate of thermal splitting is in inverse proportional to the square of the thickness of the glass to be cut. The thermal splitting rate has also been found to be dependent on the dimensions of the initial glass plate or sheet. The greater the size of the initial plate, the lower is the thermal splitting rate, resulting in a failure to split thermally a glass blank of a size exceeding 500 by 300 mm.

Apart from the low splitting speed, thermal splitting by means of a through-going crack would not provide adequately-high cutting accuracy, for the following reason. The thermal crack starts at the edge of a glass plate. By the time the crack starts, the laser beam has already moved away from the edge of the glass. Within this area, from the glass edge to the laser beam spot, a complex distribution of thermal stresses is produced in

the body of the glass and along the line of irradiation before actual splitting starts.

The moment the crack develops, it propagates in leaps through the area where the thermal stresses exceed the tensile strength of the glass. This continues until the crack reaches the area directly adjoining the laser beam spot, where high compressive stresses are concentrated in the surface layers. The crack advances to by-pass the stresses. At this point, the tensile stresses at the beginning of the crack and in the bulk of the glass under the heated surface layer combined to stop further propagation of the crack.

As the crack advances, the edges of the material on both sides of the crack are forced apart, leading to mechanical stresses which assist in further propagation of the crack. In order to ensure accurate splitting, it is essential that the crack-producing forces should be symmetrical with regard to the plane of the crack. This can be easily achieved when the crack is to be along a median plane, in which case the cracks deviate only slightly if at all from the line traced out by the laser beam spot. For this reason, as the crack advances towards a boundary of the plate, the crack curves relative to the path of the laser beam, because of the asymmetry of the thermoëlastic stresses.

As has already been mentioned, the rate of laser-induced thermal splitting is dependent on the dimensions of the plate being cut. Thus the rate of thermal splitting of a float glass plate, of 500 by 300 mm size and 3 mm thick, would not be higher than 0.5 mm/s whereas the rate of thermal splitting of a 30 by 100 mm plate of the same

material is 8 mm/s.

The rate of thermal splitting is different at different stages, that is initially; in the intermediate phase, and by the end. The speed of relative movement of the glass and of the laser beam spot should increase gradually as the crack advances through the glass.

For these reasons, it is virtually impossible to account for, and adjust properly, the rate of thermal splitting of glass or other brittle non-metallic materials by the known method. Thus, high-quality division and accuracy would not be obtained under real life conditions.

As accumulative outcome of the low speed of laser-induced thermal splitting; poor accuracy, and complexity of the control and adjustment of the thermal splitting parameters, the above method of thermal splitting by a laser beam has not found practical applications, and has been recognised as having poor prospects for the future [Ready, D *Industrial Applications of Lasers,* Moscow, MIR Publishers, 1981, pp462-463].

A known method of cutting glass tubes includes the steps of making a score or nick along the would-be line of cut, and then heating the line of cut by a laser beam, with each tube being rotated and simultaneously advanced along the beam, followed by cooling the heated line of cut [SU Inventors' Certificate No. 857 025].

Artificially decreasing the glass strength by scoring the line of cut allows the reliability of the crack development to be enhanced, and reduces the amount of energy required for thermal splitting. As a tube is

heated, compressive stresses are produced in the surface layers, and tensile stresses in the deeper layers. As the heated glass tube is sharply cooled down, its surface layers cool quickly and tend to reduce their volume, while the inner layers oppose this tendency, so that the outer part of the glass experiences tensile stresses. As the tensile strength of glass is substantially lower than its compressive strength, the use of this method of cutting glass tubes improves substantially the efficiency of thermal splitting compared with the conventional techniques of thermal splitting without local cooling of the heated zone.

However, this method of cutting glass tubes could not be applied with adequate efficiency to the splitting of brittle non-metallic materials, such as plate or sheet glass. The underlying reason is that as glass tubes are cut over their entire circumference, by their repeated rotation in a laser beam strip, gradual building up of the thermal stresses takes place. The subsequent local cooling of the line of cut results in the thermal stressing producing a crack which, with the tube rotating, extends around the tube.

If this technique were employed for the thermal splitting of sheet or plate glass, it would not yield any appreciable increase of the cutting efficiency and accuracy, because the shortcomings and limitations already discussed apply in this technique also.

An increase of the cutting speed and accuracy is partly attained by employing the technique disclosed in SU-A-1 231 813, which discloses a method of thermal splitting in which the sheet of glass or like material to

be cut is mounted on a rotary table mounted in turn on a coördinate table, and in which the progress of the crack caused by the thermal shock is monitored by a light source and detector from which data are derived to control the movement of both tables. This apparatus makes use of sphero-cylindrical focusing optics allowing an elliptical beam to be thrown on to the surface of the material being cut. This allows the heat-affected zone to be narrowed, and the temperature gradient to be increased, thus enhancing both the rate and accuracy of cutting. In this process, a coolant in the form of a jet of water entrained with air is directed at the heated zone to produce tensile stresses along the line of cut.

However, as in the other known methods of thermally splitting glass, the cutting rate attainable with this technique remains relatively low on account of the poor thermal conductivity of glass and other brittle non-metallic materials, such as glass and other ceramics, or quartz.

The present invention aims at providing a method of cutting brittle non-metallic materials by a thermal process in which the shape, direction, depth, speed and accuracy of the crack are closely controlled.

Accordingly the present invention provides a method of forming in one surface of a body of brittle non-metallic material a crack of specified depth and direction with respect to the surface, including the steps of effecting relative movement between the body and the target area at which a first beam of radiation impinges on the surface, along the intended direction of the crack; directing a stream of fluid coolant at a point on the heated surface

which is on the intended line of the crack, and which is displaced downstream from the target area by a chosen distance, and controlling the energy of the beam so that it heats the surface to a temperature below the softening point of the material.

It is expedient to select the rate of relative movement of the beam spot and the material to be cut from the equation:

$$V = k\, a(b+l)/\delta\ ,$$

where

- V is the rate of relative displacement of the heat beam and of the material;
- k is a proportionality factor dependent on the thermophysical properties of the material and the power density of the beam;
- a is the width of the beam spot on the material surface;
- b is the length of the beam spot;
- l is the distance from the rear edge of the beam spot to the front edge of the cooled zone, and
- δ is the depth of the blind crack.

This selection of the parameters of the beam, related to the cooling conditions and the splitting rate, provides for the formation in a material of given properties of a blind crack of the required depth. With the destructive tensile stresses concentrated in a narrow local zone, and with the heating of the body of the material being unnecessary the speed of cut may be increased by one hundred or more times, compared with known processes,

with both the speed and accuracy of cut being unaffected by the dimensions of the initial sheet of the material being cut. In this cutting method, with its characteristic surface heating of the material, and local cooling of the heated zone, neither the state of the opposite surface of the material being cut, nor its lateral boundaries, influence the crack-formation process. In cutting Na-K plate glass by this method, a speed of 1,000 mm/s has been achieved, with 10 μm accuracy.

It is highly expedient that the heat beam used should be a beam of coherent radiation of elliptical cross-section where it is incident on the material to be cut. The dimensions of the laser beam spot are selected to maintain the beam power density within the range of 0.3 to 20.0 x 10^6 $W.m^{-2}$, with the following proportions being observed:

$$a = 0.2 \text{ to } 2.0.h, \text{ and}$$
$$b = 1.0 \text{ to } 10.0.h,$$

where a and b are respectively the lengths of the minor and major axes of the elliptical beam spot, and

h is the thickness of the material.

These limitations, applied to the energy and geometric parameters of the laser beam spot, provide for the formation of a blind crack in materials of various thermophysical properties and of different thicknesses.

It is further expedient that the cutting operation should be preceded by preheating the cutting zone, the preheat

temperature being selected to satisfy the condition;

$$T = 0.4 \text{ to } 1.0.\Delta T,$$

where ΔT is the thermal resistance of the material to being cooled.

Preheating the surface of the material not only increases the cutting speed, but also increases the depth of the crack, which may be of importance when cutting materials of relatively great thicknesses.

In some cases, it could be expedient to reheat the line of cut after the blind crack has been produced in the material. Such reheating either increases the depth of the crack substantially or splits the material completely through. Moreover, the rate of relative displacement of the material to the beam spot during reheating may be significantly higher than during the initial process for forming the blind crack.

In cutting along a closed path, the beam should be moved tangentially to the line of cut at any point along its path.

It is further expedient, when cutting along a closed path, that, prior to cutting, the surface of the material should be scored along the path to a gradually-increasing depth, with a subsequent heating and cooling starting from the deepest part of the score.

When cutting along a closed path with relatively-small radii of curvature, the reheating should be performed with the beam off-set radially outwards of the path.

should not exceed the softening point of the material. Otherwise, if the plasticity limit of the material is exceeded, residual thermal stresses would set in after the line had been cut had been cooled, resulting in the

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Figure 3 illustrates graphically the dependence on the depth of the blind crack on the preheat temperature;

Figures 4 and 5 (Figure 5 being a sectional view taken on line V-V of Figure 4) illustrate schematically the operation of scoring the material to a gradually-increasing depth prior to cutting it along a curvilinear closed path, and

Figure 6 illustrates a decorative raised-pattern edge face produced in accordance with the present invention.

The cutting of non-metallic materials, specifically glass, under the action of thermoëlastic stresses, resides in the following. As a surface of a piece 1 of non-metallic material, such as glass (Figure 1) is heated with an incident beam of coherent radiation, considerable compressive stresses are produced in the surface layers of the material 1, which, however, do not result in its cracking or splitting. In order for the material to be cut, the following conditions should be satisfied. Firstly, the beam should be able to heat the surface of the material to be cut, that is its radiation should be at a wavelength with respect to which the material to be cut is virtually opaque. Thus, in the case of glass, the radiation should be in the infra-red range, with a wavelength in excess of 2 μm, such as the beam of a CO_2 laser, with its 10.6 μm wavelength; of a CO laser with its wavelength of about 5.5 μm, or of an HF laser with its wavelength of 2.9 μm. Secondly, as the surface of the material is being heated, its maximum temperature

should not exceed the softening point of the material. Otherwise, if the plasticity limit of the material is exceeded, residual thermal stresses would set in after the line had been cut had been cooled, resulting in the material cracking uncontrollably.

A stream or jet of a suitable coolant is directed at an area 3 of the material 1 in the wake of the advancing beam spot 2, to bring about sharp localised cooling of the surface layer along the line of cut. The temperature gradient thus produced induces tensile stresses in the surface layers of the material 1 and, as these stresses exceed the tensile strength of the material, the latter develops a blind crack 4 penetrating the material down to the parts thereof which are under compression. Hence, the blind crack 4 is formed in the material down to the interface of the heated and cooled zones, that is in the area of the maximum thermal gradient. The depth, shape and direction of the crack are determined by the distribution of the thermoëlastic stresses, which in turn are dependent on several factors.

These factors are:

- the parameters of the beam spot, namely the power density, and the dimensions and shape of the beam spot;

- the rate of relative displacement of the beam spot and the material;

- the thermophysical properties, quantity and conditions of supply of the coolant to the heated zone, and

- the thermophysical and mechanical properties of the material to be cracked, its thickness, and the state of its surface.

To optimise the cutting cycle for different materials, it is necessary to establish the proper relationship between the major parameters and variables of the cutting process.

It has been found from experiments that, depending on the dimensions of the beam spot 2 and its spacing from the area 3 on which the coolant stream falls, the speed V of the relative displacement of the beam and of the material, and the depth δ of the blind crack, are related by the expression:

$$V = k\, a(b+l)/\delta ,$$

where V is the rate of relative displacement of the beam spot and of the material;
k is a proportionality factor dependent on the thermophysical properties of the material and the beam power density;
a is the width of the beam spot;
b is the length of the beam spot;
l is the distance from the rear edge of the beam spot to the front edge of the cooled zone, and
δ is the depth of the blind crack 4.

In determining the maximum power density of the laser beam employed for cutting the material, the maximum temperature of the surface-layer of the material may not exceed its softening point. Thus, the minimum power

density value of about 0.3 x 106 $W.m^{-2}$ is acceptable for the lower-melting grades of thick glass at low thermal splitting speeds. The maximum power density value of 20 x 10^6 $W.m^{-2}$ may be used in cutting high-melting quartz glass, corundum and other materials with either a high softening point or a high value of thermal conductivity.

As the temperature of the surface of the material 1 is directly dependent on the time of its exposure to the laser beam 2, the use of a beam 2 of elliptical instead of circular cross-section extends the time of the heating of each point on the surface of the material 1 along the cutting line for the same rate of relative displacement. Hence, with a set power density of the laser beam 2, and with the same distance from the laser beam spot to the front edge of the coolant spot, which is essential for maintaining the required depth of heating of the material 2, it appears that the greater the laser beam spot is extended in the displacement direction, the greater may be the rate of the relative displacement of the laser beam spot and material.

Moreover, any significant narrowing of the heating zone 2 transverse to its cutting direction enhances the accuracy of cutting.

If the laser beam spot 2 is narrowed excessively, this might lessen the resultant thermal stress, thus threatening the splitting action. Experiments have yielded the optimized relationships between the lengths of the minor and major axes of the laser beam spot 2 of elliptical cross-section, and the thickness of the material being cut:

a = 0.2 to 20.0 h,
b = 1.0 to 10.0 h,

where	a and b	are, respectively, the lengths of the minor and major axes of the elliptical beam spot 2; and
	h	is the thickness of the material 1.

When the width of the laser beam spot 2 is less than 0.2 of the material thickness, that is if a < 0.2h, the efficiency of the cutting process is impaired on account of the diminishing value of the thermal tensile stress action in the cooling zone. Putting this right requires reducing the cutting speed and decreasing the depth of the crack 4, to say nothing of the greater probability of overheating the material along the cutting line, resulting in residual thermal stresses. On the other hand, with a > 2h, the cutting accuracy is adversely affected by the unnecessary width of the heating zone.

The reasons for stipulating the b = 1.0 to 10.0 h range of the lengths of the major axis of the laser beam spot are with b < h, the cutting speed is too low, and with b > 10 h, the cutting accuracy is impaired.

The rate of thermal splitting is in inverse proportion to the depth of the blind crack 4 being formed, that is the higher the rate of the relative displacement of the beam and material, the smaller is the depth of the crack 4. When relatively thin sheet materials are cut, of thickness from 0.3 to 2.0 mm, the depth of the microcrack 4 formed even at such high cutting speeds as 100-500 mm/s is sufficient for subsequent final splitting or breaking of adequate quality along the path. However, when

thicker plate materials 1 are cut, even low rates of relative displacement produce a shallow microcrack, making the final splitting therealong quite difficult.

Experiments have shown that the preheating of the material 1 being divided to a temperature within the range of T = 0.4 to 1.0 ΔT, where ΔT is the thermal resistance of the material to cooling, sharply increases the thermal splitting rate. Figure 2 illustrates graphically the dependence of the thermal splitting rate on the preheat temperature for common-grade plate glass, of 6 mm thickness - curve a; of 10 mm thickness - curve b, and of 25 mm thickness - curve c.

Experimental studies have proved that preheating the material to be cut to a temperature below 0.4ΔT is inefficient, for the productivity thus gained is minimal, whereas raising the preheat temperature above ΔT is ill-advisable, for when the cutting line is subsequently heated by the laser beam and cooled locally by the coolant, the threat of uncontrolled cracking of the material under the action of the thermal stress becomes real.

Beside providing for increasing the cutting speed, preheating the material has been found to increase the depth of the blind crack formed. Experiments have revealed linear dependence of the depth of the crack on the preheat temperature of the surface of the material being cut. Figure 3 of the appended drawings shows the corresponding diagrams for the plate glass mentioned above, curves d, e, f.

It has been further found that in certain cases it is

essential to reheat the cutting line either to increase the depth of the blind crack 4 (Figure 1) or to split the material completely along the line of cut. The method in accordance with the invention produces in the material 1 a blind crack or microcrack 4, which in some cases is relatively shallow. In the case of rectilinear cutting, the final division of the material 1 into blanks is performed by breaking the scored material 1 either manually or with the aid of specific mechanisms or devices. However, the manual breaking operating would not support adequately high quality of the articles obtained, and results in rejects. Furthermore, particularly great difficulties are presented by breaking out of a blank of a closed curvilinear outline. To solve this problem, the line of cut should be reheated, either by the laser beam 2 or by another suitable heat source. The thermal stresses yielded by the reheating bring about further deepening of the blind crack 4. The degree of the deepening of the crack 4 is dependent on the power of the heat source, the cutting speed, the thickness of the glass or other material being cut, and on the depth of the initial microcrack. By varying these parameters appropriately, it is possible to attain the required degree of deepening of the crack 4, up to the complete splitting.

As has already been stated, in the process of cutting along a curvilinear closed path (Figure 4), the beam 2 should be moved strictly tangentially to the cutting line at any point along the path. This is explained, in the first place, by the dependence of the thermal splitting rate on the angle ϕ between the major axis of the beam spot and the direction of its relative advance. With the major axis of the beam spot at an angle to its direction

of relative movement, the value of the displacement speed has to be reduced, down to its minimum value when the major axis of the beam spot 2 is normal to its direction of movement. When the ratio b/a of the major and minor axes of the elliptical beam 2 decreases, the difference between their effective speeds V also decreases. In the second place, the necessity of moving the beam 2 strictly tangentially to the line of cut, particularly in the course of reheating for the final splitting, is associated with the requirement that the cutting should produce a high-quality end face perpendicular to the surface of the material of the article yielded by the cutting. As the elliptical beam 2 deviates from the tangent to the cutting line, asymmetrical distribution of thermal stresses results in the plane of the crack 4 ceasing to be normal to the material surface, which in certain cases cannot be tolerated.

There is still another problem associated with cutting along a closed curvilinear path. In such cutting the actual cutting line tends to become deflected from the predetermined path in the area where the path meets itself, which is because of the combination of similar tensile stresses at present at the starting point of the crack 4. To preclude this, prior to starting the cutting, a score or nick 5 (Figures 4, 5) of a gradually-increasing depth is made along the cutting line. The ensuing successive heating and cooling of the material being cut starts from where the score 5 is at its deepest part 6 of the score 5. Thus, the thermal crack would commence at this deepest part 6 of the score 5, and the closing of the path would begin at a point 7 where the depth of the score 5 is minimal. This allows the tensile stresses to be reduced and virtually eliminates the

crooking of the cutting line as a curvilinear outline is closed.

It has been found from experiments that the optimum length of the score 5 can be determined from the expression:

$$V = k\, a(b+l)/\delta\ ,$$

where V is the rate of relative displacement of the beam spot and of the material;
k is a proportionality factor dependent on the thermophysical properties of the material and the beam power density;
a is the width of the beam spot;
b is the longitudinal cross-sectional size of the beam spot 2;
l is the distance from the rear edge of the beam spot to the front edge of the cooled zone, and
δ is the depth of the blind crack 4.

In this, as has already been mentioned, the heating and subsequent cooling of the cut line are commenced at the deepest point 6 of the score 5, that is when the centre of the beam spot 2 approaches the deepest point 6, or else when it is spaced by at least a distance c from the extreme end of the score. Experiments have yielded the optimised range of the values of the distance c from the centre of beam spot 2 to the extreme end of the score at the moment when the heating is started, expressed as follows:

$$0 \le c \le l/2.$$

Furthermore, it is essential that the score 5 should be a narrow relatively-deep single depression or nick, and not a scratch with longitudinal and transverse microcracks that would impair the quality of the divided surface.

When the cutting is conducted along a curvilinear outline with relatively small curvature radii, the reheating is preferably performed with the heat beam offset from the centre towards the border of the curved outline. The expedience of this technique is explained as follows. In rectilinear cutting, the fields of thermoëlastic stresses remain permanently symmetrical with respect to the path of the displacement both during the primary heating, as the microcrack is being formed, and that in the course of the reheating when the material is finally split along the microcrack. However, when the cutting is along the curve outline, this symmetry of thermoëlastic stresses is disturbed by the influence of the already-heated volumes of the material within the curve, and this influence is the greater, the smaller the radius of the curvature of the curve. This influence becomes particularly pronounced during the reheating of the curved path, tending to deflect the crack from extending normal to the surface of the material, and thus adversely the affecting the cutting accuracy and the cut face quality after the removal of the surplus material. Therefore, to enhance the cutting accuracy and cut face quality in cutting along small curvature radii, the beam should be preferably offset from the curve towards the border during the reheating. The value of this offset depends on the cutting speed, the radius of curvature, the size of the beam spot, and the thickness of the material, and is found from experience.

In most cases of producing articles of glass and like non-metallic materials, in the electronics, instrument-making and like industries, strict requirements are put on the geometrical dimensions and quality of their edge faces, such as the requirement of strict perpendicularity of the plane of a crack to the surface of the material itself. The above-described techniques of performing the method in accordance with the invention are specifically aimed at optimising the solution of this problem. However, there are other fields of technology where the quality of the edge faces of articles of glass and like non-metallic material is expected to meet quite different requirements, such as when it is desirable to produce facetted or slanting faces, or else an edge face with a decorative raised pattern. To attain this, it is necessary in each case to alter the dynamic distribution of thermoëlastic stresses in the cutting zone by redistributing the energy asymmetrically with respect to the cutting line, and also by aiming at a required profile of distribution of the fields of thermoëlastic stresses by some appropriate offsetting of the point of impact of the coolant relative to the beam spot.

Thus, a decorative raised-pattern edge face can be produced when the symmetry of the thermal field with respect to the path of displacement is disturbed by rotating the beam 2 (Figures 4, 5) of elliptical cross-section through a chosen angle relative to the speed vector. The thermal stresses thus produced, with their asymmetrical distribution with respect to the plane included in the centre of the beam spot 2, and perpendicular to the displacement direction, lead to discrete splitting of the material in a decoratively-shaped contour (Figure 6) along the line of heat.

A decorative edge face is produced with enhanced reliability when a cutting line is marked out in advance as a blind thermal crack along the required path by the previously-described techniques, and then this cutting line is reheated with the beam of elliptical cross-section turned at an angle relative to the cutting line. This results in the superpositioning of the tensile stresses concentrated at the edge of the microcrack and the stresses produced in the reheating of the cutting line with the asymmetrical beam. The dynamics of the distribution of the stresses through the volume of the material are of a complex nature dependent on such factors as the elliptical beam spot 2, its angle ϕ relative to the displacement direction, the effective power density of the beam, the thickness of the glass or other material, and the rate of relative displacement of the beam and the material.

The splitting of the material 2 in a decorative complex profile takes place as follows. As the inclined beam 2 of elliptical cross-section moves relative to the material during reheating, an inclined crack is formed, propagating at an angle to the direction determined by the initial microcrack. This propagation of the crack 4 (Figure 1) occurs in steps in those areas in which the stresses exceed the ultimate strength of the material. As the stresses diminish in value with distance from the microcrack, dependent on the thermal splitting parameters, the development of the crack ceases, while the onset of tensile stresses at the newly formed crack alters the profile of the resultant stresses, so that the inclination of the crack changes from that of the initial crack. As the beam moves on, this crack-formation cycle repeats itself.

The existence of the initial microcrack is not mandatory for producing a decorative edgeface. However, when the microcrack already exists, a slanting facet is formed which, in addition to enhancing the appearance of the edge face of the article, precludes a person handling the article from having his or her hand cut in advertently by a sharp edge.

The decorative working of the edge faces of glass articles by thermal splitting may be employed for the decorative finishing of artistic items and manufactured consumer goods made of glass, such as mirrors, components of luminaires, colour music panels and the like, instead of complicated and labour-intensive operations of diamond cutting and faceting followed by chemical polishing in a hydrofluoric acid solution.

The method of the present invention is performed as follows. An initial piece of blank of a material, such as a glass sheet, is placed onto the heated panel of a coördinate table. The table is actuated to move with the blank, and a scoring mechanism including diamond point is urged with an increasing load against the glass surface to score it. The beam of a laser is directed through a focusing lens on to the glass surface, to strike the line of score. A jet of an air/water mixture (the coolant) is turned on at the moment when the nozzle points at the deepest part of the score. A microcrack is formed at the spot where the coolant jet hits the glass, and develops along the line of cut as the blank moves relative to the laser beam and to the jet nozzle. As the cutting line prescribed by the developing microcrack closes to form an endless path, the supply of coolant to the heated zone is discontinued. However, movement of the blank and heating

of the cutting line with the laser beam is continued for another full revolution, so that the glass becomes split along the line marked out by the microcrack. When the crack propagates through the thickness of the material along the endless path, the laser beam is turned off, the coördinate table is halted, and the blank is removed from the table. With the surplus material removed, the required article is obtained, that is a precision-cut glass disk.

Examples

Sheet glass 1.2 mm thick was cut using a 25 W CO_2 laser of LGN-703 Type. Disks 31.2 mm in diameter were cut out, to be used as watch glasses. The glass blank was preheated to 70°C. The laser beam was focused by a spherocylindrical lens into a beam of elliptical cross-section, of 1.4 x 3.0 mm dimensions. A 4 mm score along the cutting line was made by a diamond pyramid of 120° angle at the apex. The cutting speed was 20 mm/s. The cutting accuracy was 10 μm.

In addition to cutting plate and sheet glass, the disclosed method was employed for cutting such non-metallic materials as single-crystal and fused quartz, glass ceramic, leucosapphire, ceramics.

The results of the testing of the disclosed method of cutting non-metallic materials in the cutting of different grades of glass and quartz with varying parameters of the laser beam and other process parameters are summed up in Table 1.

An analysis of the testing results suggests the following

conclusions.

The efficiency of the cutting process in terms of the cutting speed and accuracy, the quality of the edge face of the material produced by the cutting is influenced not only by the major parameters of the process, such as the longitudinal and transverse dimensions of the laser beam spot on the material surface, the beam power density, the location and conditions of the supply of the coolant to the heated zone, the thickness and properties of the material being divided, but also by the strict observance of the prescribed relationships of these parameters.

In this, in dependence on the combination of the above parameters, high-quality cutting can be attained, yielding a smooth flawless edge face which is strictly normal to the material surface. As demonstrated by Examples 20-22 (marked with '*' in Table 1), when the line of cutting defined by a 0.6 mm deep microcrack was reheated with a laser beam of elliptical cross-section directed at an angle to the advance direction, a raised pattern decorative edge was produced.

Examples 17-19 (marked with '**' in Table 1() refer to a glass grade with thermal resistance ΔT - 120°C, i.e. in these cases the temperature T of preheating the glass surface was related to the thermal resistance value, as follows: in Examples 17, 18, 19, respectively, $T = 0.4\Delta T$, $T = 0.7\Delta$, $T = \Delta T$.

It can be seen from the Examples that as the cutting speed was increased, the depth of the crack grew.

TABLE 1. Results of Testing the Method of Cutting Non-Metallic Materials

Ex.No.	Material	Working Parameters: Heat beam parameters: a, mm	b, mm	Q, x 10^6 W/m^2	h, mm	l, mm	V, mm/s	δ, mm	T, °C	φ, deg.	k,	k/Q	Test Results: Cutting accuracy, mm	Q-ty of rejects by residual thermal stresses, %	Repeata-bility %
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	Glass	2	11	1.5	6	20	16	0.6	20	0	0.15	0.1	0.05	0	100
2	Glass	2	11	1.5	5	17	16	0.6	20	0	0.14	0.09	0.05	0	100
3	Glass	2	11	1.5	5	17	10	1.0	20	0	0.18	0.12	0.05	0	100
4	Glass	2	11	1.5	5	17	6	1.3	20	0	0.14	0.09	0.05	10	100
5	Glass	4.5	17	0.6	6	28	7	1.75	20	0	0.06	0.1	0.1	0	100
6	Glass	4.5	17	0.6	6	28	9.3	1.4	20	0	0.06	0.1	0.1	0	100
7	Glass	4.5	17	0.6	6	28	14	1.3	20	0	0.09	0.15	0.1	0	100
8	Glass	4.5	17	0.6	6	28	18.8	1.0	20	0	0.09	0.15	0.1	0	100
9	Glass	4.5	17	0.6	6	35	7	2.1	20	0	0.06	0.1	0.1	0	80
10	Glass	4.5	17	0.6	6	35	9.3	1.35	20	0	0.05	0.08	0.1	0	92
11	Glass	8.6	14.3	0.3	6	10	6	3.0	20	0	0.1	0.33	0.5	0	40
12	Glass	1.4	10.7	2.2	3	4	39	0.3	20	0	0.57	0.26	0.01	0	100
13	Quartz	1.5	1.5	20	3	4	20.4	0.08	20	0	0.2	-	0.05	10	90
14	Quartz	1.4	1.4	22	3	4	24.2	0.03	20	0	0.12	-	0.2	88	20
15	Glass	1.2	23	1.0	6	4	14	0.5	20	0	0.22	0.22	0.1	18	70
16	Photoglass	4.6	4.6	1.5	2.3	4	18	0.35	20	0	0.16	0.11	0.5	0	50
17	Glass	2	11	1.5	6	18	18	0.6	48**	0	-	-	0.05	0	100
18	Glass	2	11	1.5	6	18	45	0.82	84**	0	-	-	0.05	0	100
19	Glass	2	11	1.5	6	18	120	1.04	120**	0	-	-	0.05	33	60
20	Float Glass	2.5	8	1.4	6	-	18	0.6*	20	3	-	-	-	0	50
21	Float Glass	2.5	8	1.4	6	-	15	0.6*	20	10	-	-	-	0	100
22	Float Glass	2.5	8	1.4	6	-	12	0.6*	20	45	-	-	-	0	64

CLAIMS

1. A method of forming in one surface of a body of brittle non-metallic material a crack of specified depth and direction with respect to the surface, including the steps of:
effecting relative movement between the body and the target area at which a first beam of radiation impinges on the surface, along the intended direction of the crack;
directing a stream of fluid coolant at a point on the heated surface which is on the intended line of the crack, and which is displaced downstream from the target area by a chosen distance, and
controlling the energy of the beam so that it heats the surface to a temperature below the softening point of the material.

2. A method as claimed in Claim 1, including imparting to the beam a non-circular cross-section where it impinges on the body, the target area having a longer direction along the crack line than normal to it.

3. A method as claimed in Claim 2, in which the target area is substantially elliptical in shape.

4. A method as claimed in any preceding claim, in which at least the volume of the body containing and bordering the intended line of the crack is preheated.

5. A method as claimed in Claim 4, in which the body is preheated to a chosen temperature related to the

desired depth of the crack.

6. A method as claimed in any preceding claim, in which the body is heated, after the crack has been formed, along the line of the crack and to an extent sufficient to cause the depth of the crack to increase further.

7. A method as claimed in Claim 6, in which the post heating is effected by means of a second beam of radiation moved along a path coincident with, or parallel to, the crack.

8. A method as claimed in any preceding claim, in which the part of the body surface at which the first beam is initially incident is spaced inwardly from the borders of the body.

9. A method as claimed in Claim 8, in which the path of the first beam traces out a closed curve on the body surface, and in which, when the target area of the beam is non-circular, the direction of the major axis of the target area is kept at a constant orientation to the tangent at the point on the curve which lies at the centre of the target area.

10. A method as claimed in Claim 9, in which the major axis is coincident with, or parallel to, the said tangent.

11. A method as claimed in Claim 9, in which the major axis extends at a fixed angle to the said tangent.

12. A method of forming in a body of brittle non-

metallic material a crack of specified general shape, including the steps of:
effecting relative movement between the body and the target area at which a first beam of radiation impinges on the surface of the body, along the intended direction of the crack;
directing a stream of fluid coolant at a point on the heated surface which is on the intended line of the crack, and which is displaced downstream from the target area by a chosen distance;
making the target area substantially elliptical shape, with the major axis of the target area extending at a substantially-fixed angle to the tangent to a point on the intended path of the crack lying within the target area, and
controlling the energy of the beam so that it heats the surface to a temperature below the softening point of the material.

13. A method as claimed in any preceding claim in which, when the path of the intended crack is to form a closed curve, the surface of the body is scored along an incremental part of the path, with the depth of the score being different at opposite ends thereof, and in which the first beam of radiation is initially directed at that part of the score which is of greater depth.

14. A method as claimed in claim 13, including making the score line with a sharp point of hard material which is able to gouge out material from the surface of the body to a predetermined depth.

15. A method as claimed in any preceding claim, in which

the rate of relative displacement of the beam and of the material satisfies the expression:

$$V = k\ a(b+l)/\delta\ ,$$

where V is the rate of relative displacement of the beam spot and of the material;
k is a proportionality factor dependent on the thermophysical properties of the material and the beam power density;
a is the transverse size of the heat beam spot on the material surface;
b is the longitudinal size of the heat beam spot on the material surface;
l is the distance from the rear edge of the heat beam spot to the front edge of the cooling zone, and
δ is the depth of the blind crack.

16. A method as claimed in Claim 15, in which with the beam is of coherent radiation and is of elliptical cross-section, the size of the laser beam spot satisfying the condition of maintaining the beam power density within the range of $(0.3 - 20.0) \times 10^6$ $W.m^{-2}$, with the following proportions being observed:

$$a = (0.2 - 2.0)\ h,$$
$$b = (1.0 - 10.0)\ h,$$

where a and b are, respectively, the lengths of the minor and major axes of the ellipse; and

h is the thickness of the material.

17. A method as claimed in Claims 15 or 16, in which the cutting operation is preceded by preheating the material to a temperature satisfying the condition:

$$T = (0.4 - 1.0)\ \Delta T,$$

where ΔT is the thermal resistance of the material to cooling.

18. A method of cutting non-metallic materials, specifically glass, under the action of thermoelastic stresses produced by heating the line of cutting by a heat beam, with relative displacement of the beam and of the material and with local cooling of the heated zone, characterised in that the heating is effected to a temperature short of the softening point of the material, with the rate of the relative displacement of the heat beam and of the material and the spot of the local cooling of the heated zone being selected to satisfy the condition of forming in the material a blind dividing crack.

19. A method as claimed in claim 18, characterised in that the rate of the relative displacement of the beam and of the material is found from the expression:

$$V = k\ a(b+1)/\delta\ ,$$

where V is the rate of relative displacement

of the heat beam and of the material;

k is a proportionality factor dependent on the thermophysical properties of the material and the heat beam power density;

a is the transverse size of the heat beam spot on the material surface;

b is the longitudinal size of the heat beam spot on the material surface;

l is the distance from the rear edge of the heat beam spot to the front edge of the cooling zone, and

δ is the depth of the blind dividing crack.

20. A method as claimed in Claim 19, characterised in that with the heat beam used being a laser beam of elliptical cross-section, the size of the laser beam is selected to satisfy the condition of maintaining the beam power density within the range of (0.3-20.0) x 10^6 $W.m^{-2}$, with the following proportions being observed:

$$a = (0.2 - 2.0)\ h,$$
$$b = (1.0 - 10.0)\ h,$$

where a and b are, respectively, the lengths of the minor and major axes of the ellipse; and

h is the thickness of the material.

21. A method as claimed in Claims 18, 19 and 20, characterised in that the commencing of the cutting

operation is preceded by preparing the cutting zone by way of preheating the material, the preheating temperature being selected to satisfy the condition:

$$T = (0.4 - 1.0)\ \Delta T,$$

where ΔT is thermal resistance of the material in cooling.

22. A method as claimed in Claims 18, 19, 20 and 21, characterised in that with the blind dividing crack having been produced in the material, the reheating of the cutting line is performed.

23. A method as claimed in Claims 18, 19, 20, 21 and 22, characterised in that in cutting along a closed curvilinear outline, the heat beam of elliptical cross-section in the course of the displacement is indexed tangentially to the line of cutting at any point of the curvilinear outline.

24. A method as claimed in Claims 18, 19, 20, 21 and 22, characterised in that, prior to the cutting, the surface of the material along the cutting line is scored to a gradually increasing depth, with the subsequent heating and cooling being performed successively, starting from the deepest point of the score.

25. A method as claimed in Claims 23 and 24, characterised in that, when cutting along a curvilinear outline with relatively small curvature radii, the reheating is performed with the heat beam being offset from the centre toward the border of

the curvilinear outline.

26. A method as claimed in Claims 23, 24 and 25, characterised in that, in order to control the shape and direction of the development of the dividing crack, the heating is conducted with a heat beam of which the energy is redistributed along the path of its displacement, while also controlling the position of the cooling zone on the surface of the material with respect to the heat beam position.

27. A method as claimed in Claims 18, 19, 20, 21, 22, 23, 24, 25 and 26, characterised in that, in order to produce articles with a decorative raised-pattern edge, the heating is conducted with a heat beam of elliptical cross section, with its major axis being turned relative to the path of the displacement at an angle ϕ within a 3-45° range.

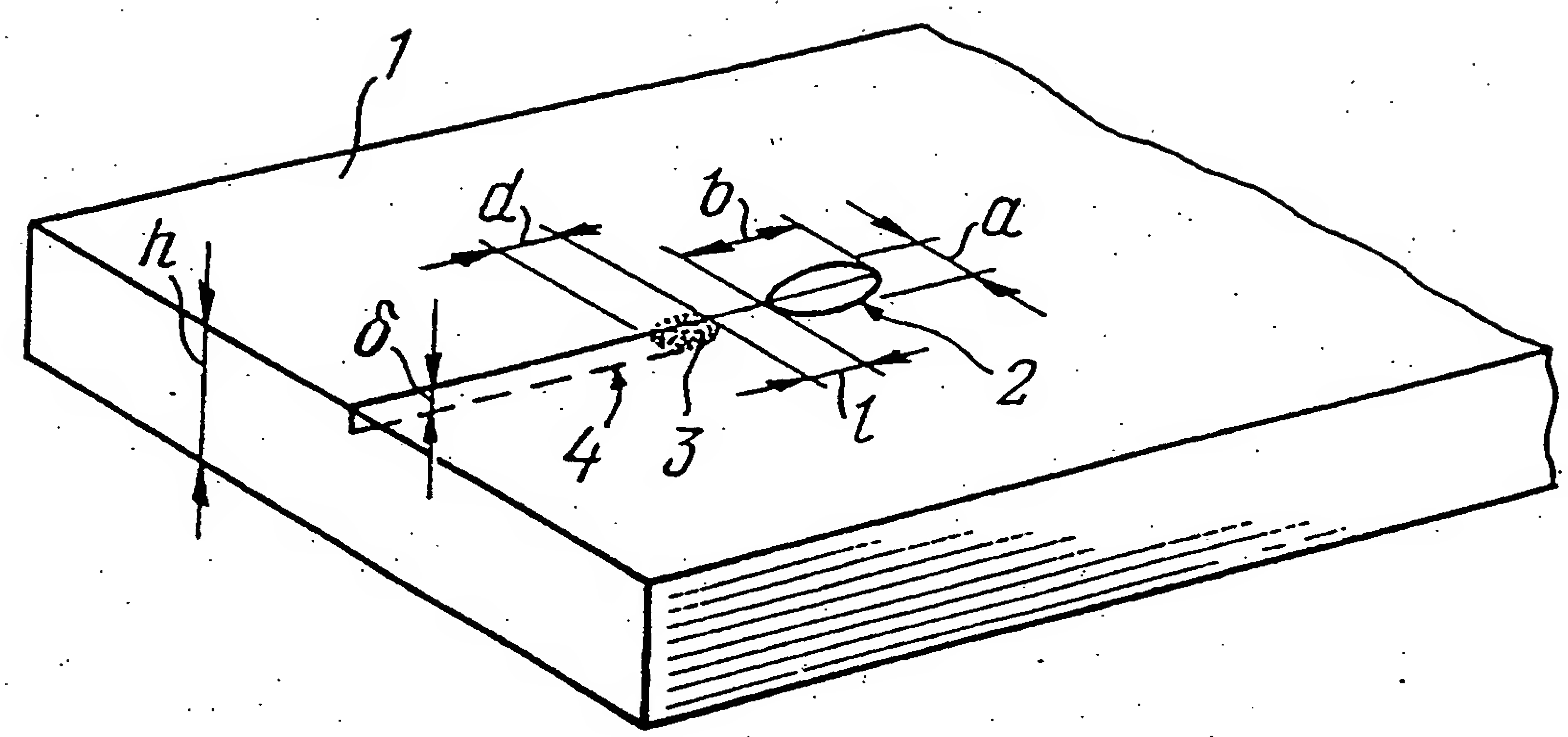
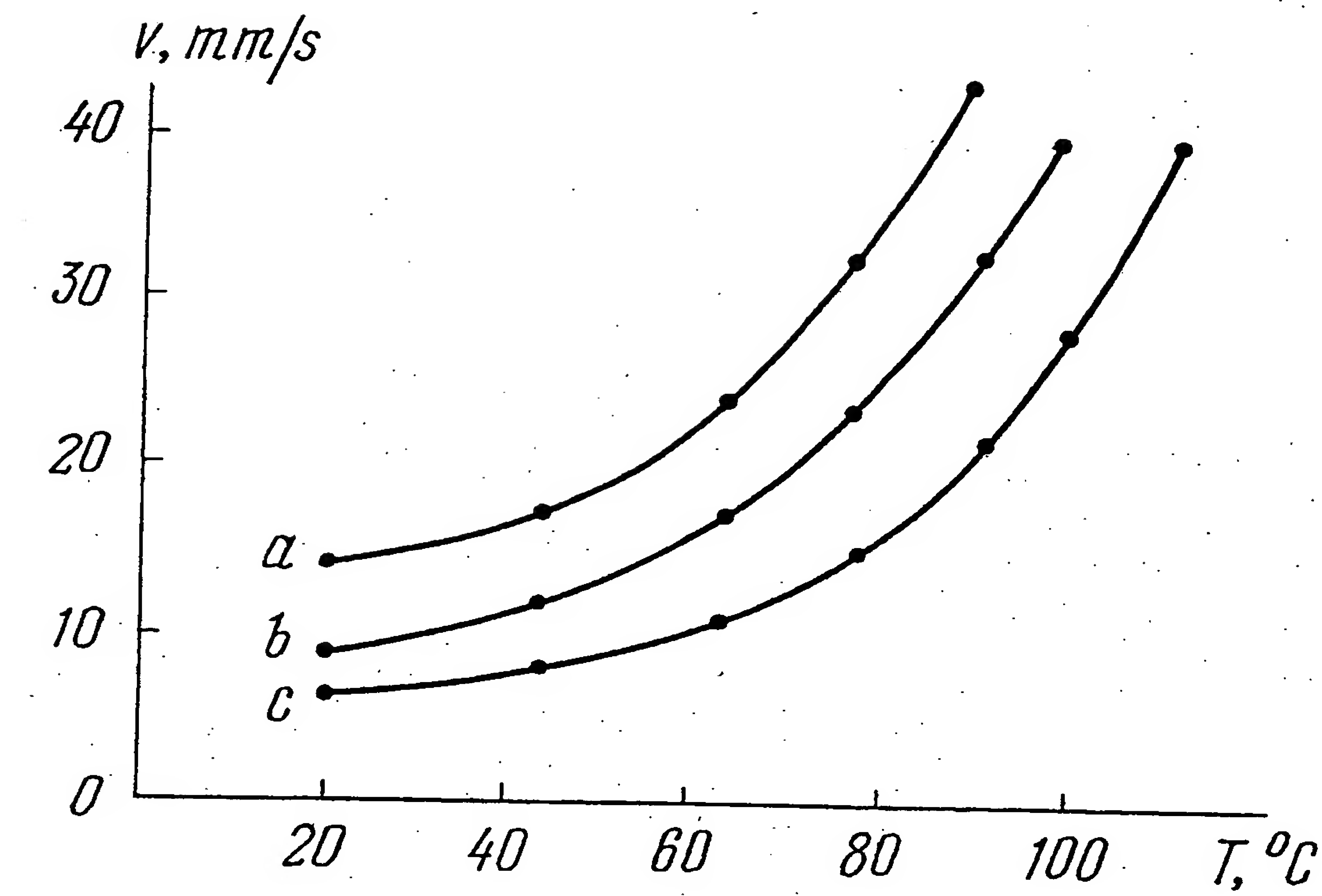


FIG.1


V, mm/s
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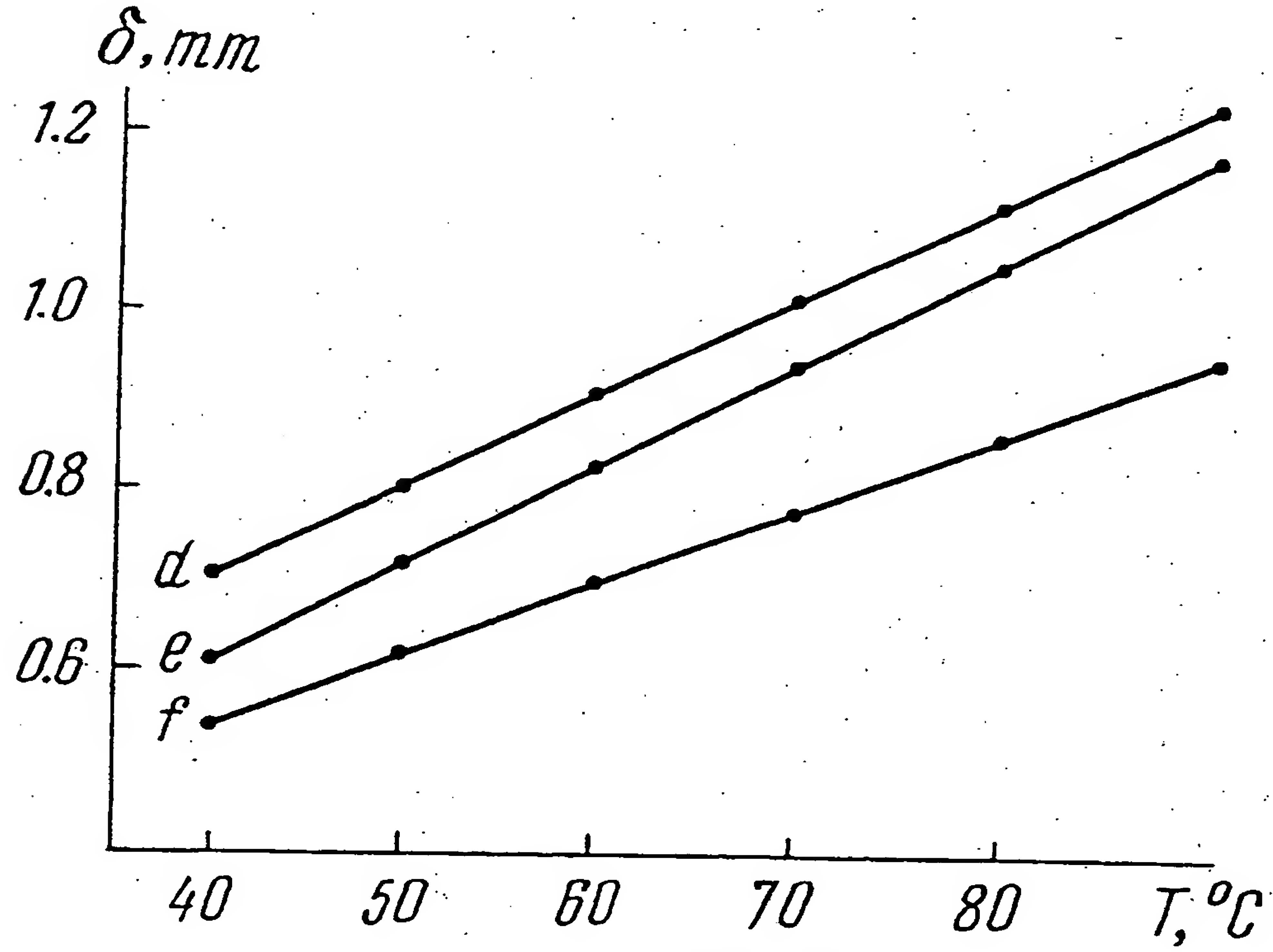
30
20
10
0
a
b
c
20
40
60
80
100
T, °C

FIG.2


δ, mm
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0.8
0.6
d
e
f
40
50
60
70
80
T, °C

FIG.3

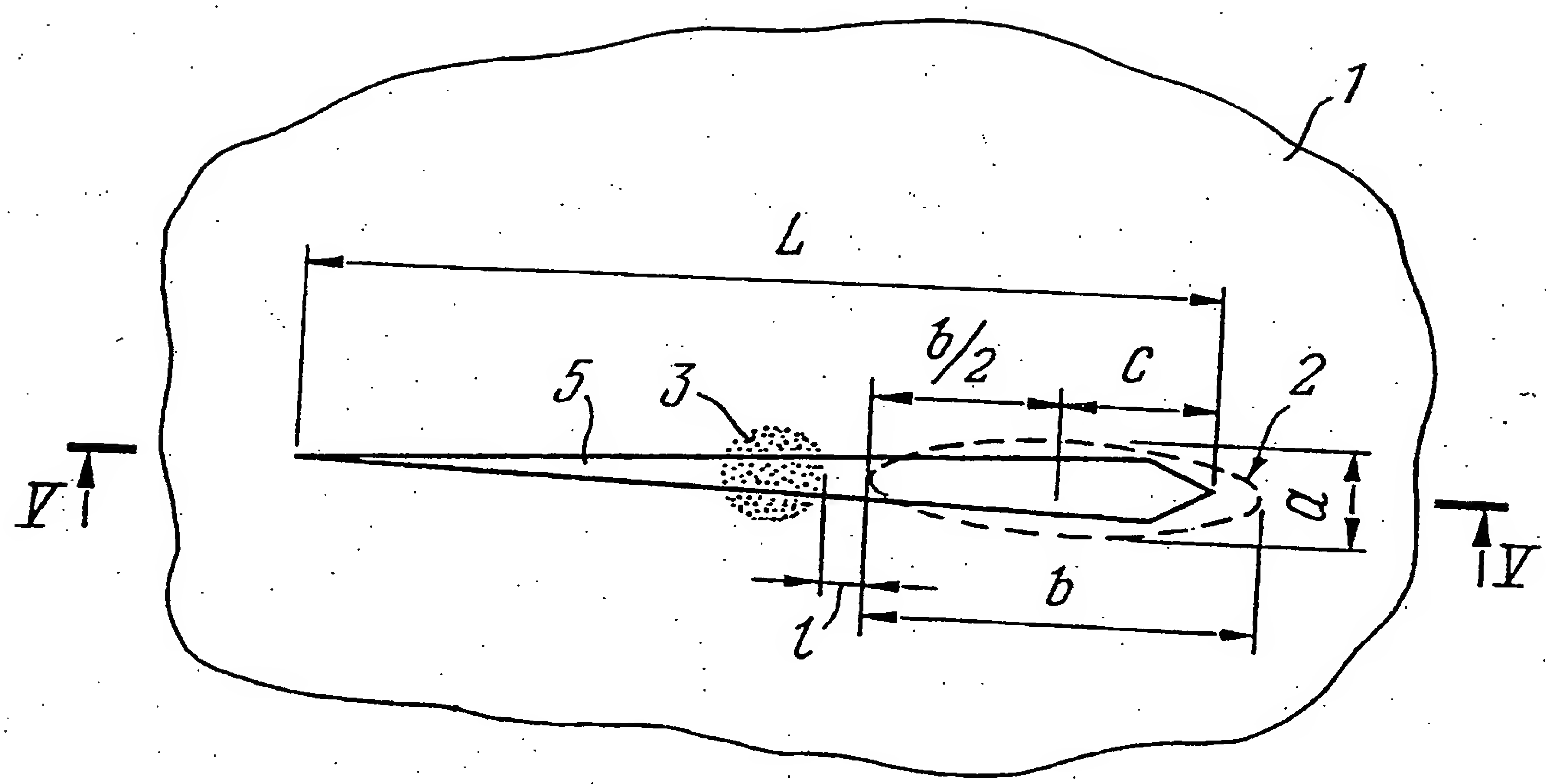

FIG.4

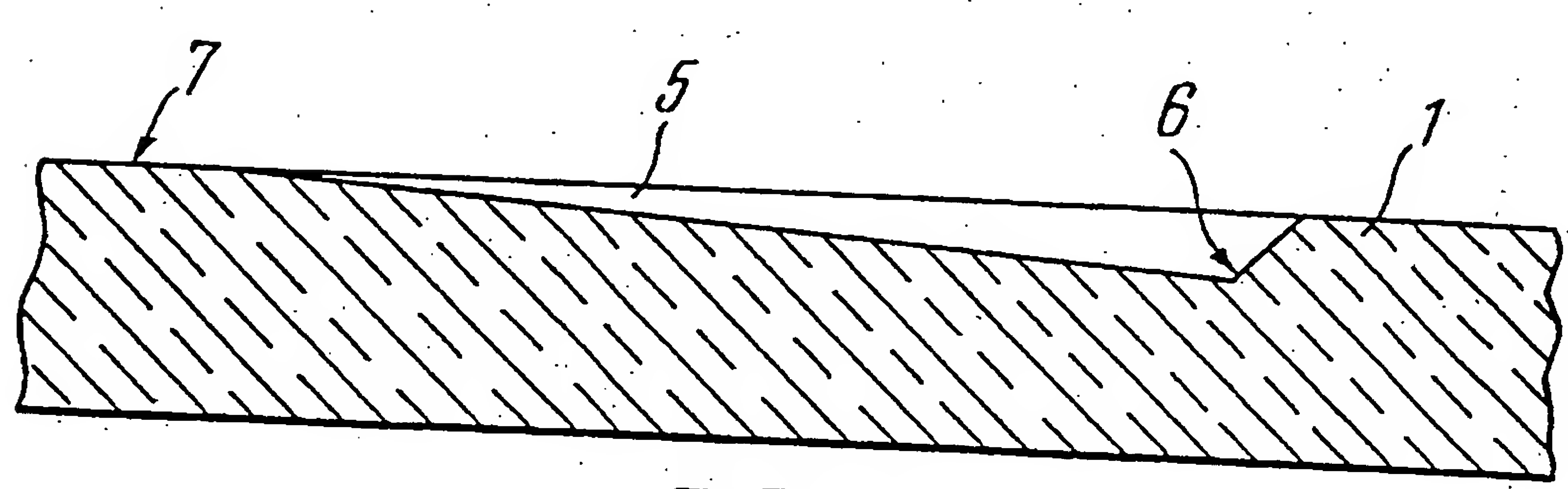

FIG.5

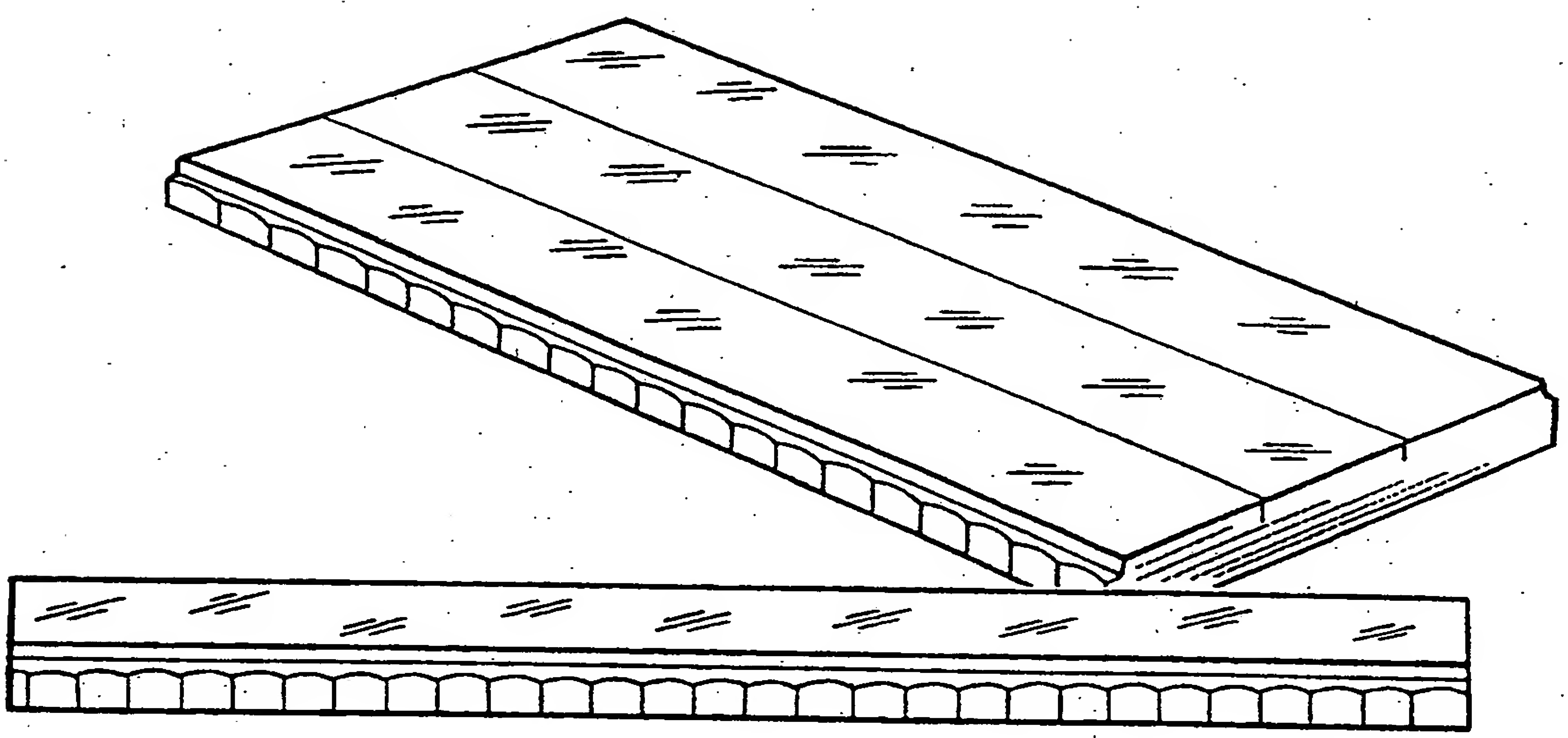

FIG.6

INTERNATIONAL SEARCH REPORT

International Application No PCT/GB 93/00699

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all)[6]

According to International Patent Classification (IPC) or to both National Classification and IPC

Int.Cl. 5 C03B33/09; B26F3/00; B26F3/06; B23K26/00
B28D1/22

II. FIELDS SEARCHED

Minimum Documentation Searched[7]

Classification System	Classification Symbols
Int.Cl. 5	C03B ; B26F ; B23K ; B28D

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched[8]

III. DOCUMENTS CONSIDERED TO BE RELEVANT[9]

Category °	Citation of Document, [11] with indication, where appropriate, of the relevant passages [12]	Relevant to Claim No.[13]
X	DE,A,1 244 346 (MENZEL) 13 July 1967 see the whole document ---	1,12,18
X	DE,B,2 813 302 (FRAUNHOFER-GESELLSCHAFT ZUR FÖRDERUNG DER ANGEWANDTEN FORSCHUNG E.V.) 11 January 1979 see the whole document ---	1,12,18, 26
X	GB,A,2 139 615 (GLAVERBEL) 14 November 1984 see the whole document ---	1,12,18
A	FR,A,2 228 040 (COMMISSARIAT A L'ENERGIE ATOMIQUE) 29 November 1974 see the whole document ---	1,12,18

-/--

° Special categories of cited documents : [10]

"A" document defining the general state of the art which is not considered to be of particular relevance

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"&" document member of the same patent family

1

IV. CERTIFICATION

Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report
12 JULY 1993	31. 07. 93
International Searching Authority	**Signature of Authorized Officer**
EUROPEAN PATENT OFFICE	VAN DEN BOSSCHE W.

III. DOCUMENTS CONSIDERED TO BE RELEVANT (CONTINUED FROM THE SECOND SHEET)		
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A	FR,A,2 202 856 (GLAVERBEL-MECANIVER) 10 May 1974 see the whole document ---	1,12,18
A	US,A,3 610 871 (WESTERN ELECTRIC COMPANY) 5 October 1971 see the whole document ---	1,12,18
A	US,A,3 629 545 (GRAHAM) 21 December 1971 see the whole document -----	1,12,18

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The members are as contained in the European Patent Office EDP file on
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		FR-A- 1598452	06-07-70
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		NL-A- 6818043	23-06-69

For more details about this annex : see Official Journal of the European Patent Office, No. 12/82